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US Army Corps of Engineers®
New Orleans District

Hydroperiod Modeling Study

Inner Harbor Navigation Canal
Proposed Barrier
Golden Triangle Marsh

26 June 2008

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U.S. Army Corps of Engineers
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Our Ref.:
NL990042.0000

Date:
26 June 2008

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1. Introduction

1.1 Purpose of Study

This Hydroperiod Modeling Study (Study) investigates the spatial and temporal extent of tidal inundation in the “Golden Triangle Marsh” area at the confluence of the Inner Harbor Navigation Canal (IHNC), Gulf Intracoastal Waterway (GIWW), and the Mississippi River Gulf Outlet (MRGO), as shown in Figure 1. The Study area for this hydroperiod analysis is comprised of a triangular marsh that straddles the border of Orleans and St. Bernard parishes, Louisiana. The area of concern is bounded on the east by Lake Borgne; on the south and west by the MRGO; and on the north and west by the GIWW. For the purposes of this study, the term “hydroperiod” is defined as the period of time during which a wetland is covered by water. This study will develop hydroperiod data for various design alternatives for the proposed IHNC barrier hurricane protection project. The data will be used to evaluate the effects of the proposed alternatives on the local tidal regime.

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1.2 Authority and Acknowledgments

This Study has been performed as part of a larger effort, to ensure that the IHNC Barrier hurricane protection project complies with the National Environmental Policy Act (NEPA) (42 United States Code 4321 et seq.)

In addition to members at ARCADIS, engineers and scientists from Ayres Associates, Inc., and the University of Notre Dame engaged in integral roles for this study. Dr. John Atkinson and Dr. Joannes Westerink are the points of contact for the two organizations, respectively.

The hydrologic and hydraulic analyses for this Study have been funded by the U.S. Army Corps of Engineers (USACE), New Orleans District (MVN), and Hurricane Protection Office (HPO).

2. Engineering Methods

State-of-the-art coastal ocean hydrodynamic analysis methods were used to determine the tidal hydroperiod as required by the HPO in support of providing NEPA compliance. The modeling system for the Study was established by fine-tuning existing models used previously for hurricane storm surge analysis in Southern Louisiana for the Louisiana Coastal Protection and Restoration project, as well as the recent flood insurance rate map modernization study conducted by the Federal Emergency Management Agency (FEMA) (USACE 2008; Westerink et al. 2007). Utilizing the existing SL15 Advanced Circulation Model (ADCIRC) grid as a starting point, this Study did the following:

(a) Created ADCIRC meshes representing five configurations of the flow structures at the GIWW, MRGO/Bayou Bienvenue, MRGO/Bayou La Loutre confluence to evaluate the impact that proposed barriers will have on hydroperiod in the marsh adjacent to the proposed IHNC barrier hurricane protection project, predominantly between Paris Road and the proposed IHNC barrier.

(b) Ran each of the five geometries constructed in task (a) on 30-day tidal simulations (subsequent to an 18-day spin-up). The 30 days of the simulation were chosen to capture both spring and neap tides for tidal conditions in September 2007.

(c) Ran 1-day simulations (subsequent to a half-day ramp) on each of the five geometries constructed in task (a) to capture the wind effects at steady state. Each geometry was exercised via constant 10 miles per hour (mph) winds from both the east and the west.

The following alternative geometries were evaluated:

- Scenario 1 – existing conditions (Figure 1);

- Scenario 2 – existing conditions with MRGO closure at Bayou La Loutre (shown on Figure 2). The MRGO closure at Bayou La Loutre is included at 4.92 feet NAVD88 (2004.65), which is the same elevation as the La Loutre ridge to the east of the channel. This scenario will be used as a base condition for comparison to all other scenarios;

- Scenario 3 – existing conditions with MRGO closure at Bayou La Loutre and the IHNC barrier in place with a 64-foot opening at Bayou Bienvenue and 170-foot opening at the GIWW. The channel bottoms at the openings are modeled as the existing depths in the channels, which are 41.5 feet in the GIWW and 9.8 feet in Bayou Bienvenue. Barriers positioned over the marsh in the study area are modeled as non-overtopping;

- Scenario 4 – existing conditions with MRGO closure at Bayou La Loutre and the IHNC barrier in place with a 128-foot opening at Bayou Bienvenue and 340-foot opening at the GIWW. The channel bottoms at the openings are modeled as the existing depths in the channels, which are 41.5 feet in the GIWW and 9.8 feet in Bayou Bienvenue. Barriers positioned over the marsh in the study area are modeled as non-overtopping; and

- Scenario 5 – existing conditions with MRGO closure at Bayou La Loutre and the IHNC barrier in place with a closure at Bayou Bienvenue and 170-foot opening at the GIWW. The channel bottom at the opening of the GIWW is modeled as 41.5 feet, which is the existing depth in the channel. Barriers positioned over the marsh in the study area are modeled as non-overtopping.

All five scenarios are modeled with the tide gates closed at Bayou Bienvenue and Bayou Dupre west of the MRGO along the federal levee. Through discussions with members of HPO, it was decided that the influence of the proposed IHNC structures on the marsh in the Golden Triangle was most critical to investigate. The effort required to properly model the marsh areas enclosed in the St. Bernard Parish levee system was deemed too time consuming given the time constraints of the Study. In addition, no discharge information at the gates of Bayou Bienvenue and Bayou Dupre along the federal levee system was incorporated into the model. Rather, non-overtopping levee conditions were assumed, This was done due to the limited discharge information at those locations, as well as the assumption that the discharge rates would have minimal effects on the tidal regime in the area.

3. Model Parameters

3.1 Modeling Strategy and System

The coastal hydrodynamic modeling methods used to determine water levels were selected and implemented based on the following criteria:

- An extensive understanding of the physical system as a whole and its individual consequential components;
- Inclusion of all significant physical processes affecting water levels;
- Full consideration of the interaction between physical processes;
- Characterization of forcing functions that correspond with real world observations;

- Accurate definition of boundary conditions; and

- Generation of discrete numerical grids to resolve the physical and energetic processes consistently and accurately within the models.

Thus, the goal is to implement a modeling capability that represents the basic physics of the system as it is observed in nature and does not require ad hoc model tuning. Previous studies have shown that the SL15 mesh is capable of rendering this goal. The SL15 domain, including the North Atlantic and Gulf of Mexico, can be seen on Figure 3. Specific details of the modeling system, such as geographic and vegetative characteristics, can be found in the FEMA report (Westerink et al. 2007a).

The need for highly accurate results in the area of concern called for a considerable increase in model resolution from the SL15 model. For all five hydroperiod scenarios, the resolution was increased as high as 8 meters at Bayou Bienvenue and 15 meters at the GIWW to accurately convey tides through the narrow openings. Topographic and bathymetric values were interpolated from the original SL15 mesh in the area of increased resolution. The only exception to this was a deepening of Bayou Bienvenue to a more accurate depth of 3 meters in the hydroperiod analysis meshes. Sparse survey data described by HPO exhibited depths of approximately 10 feet in the channel. Thus, values of 3 meters were applied in order to assume the same channel characteristics used by other models utilized for analysis of the area, Figures 4 through 7 display the mesh resolution and topographic contours for both the SL15 mesh and hydroperiod analysis meshes. Note the increased resolution at the openings of the GIWW and Bayou Bienvenue in the hydroperiod analysis meshes, as well as the deepened bayou and inclusion of the proposed IHNC barrier.

3.2 ADCIRC Model Description

ADCIRC-2DDI, the two-dimensional, depth-integrated implementation of the ADCIRC coastal ocean model, was used to perform the hydrodynamic computations in this study (Luettich et al. 1992; Westerink et al. 1992; Westerink 1993; Luettich and Westerink 2004). The model uses the depth-integrated barotropic equations of mass and momentum conservation subject to the incompressibility, Boussinesq, and hydrostatic pressure approximations.

3.3 Grid Definition

In the same fashion as the SL15 mesh, the hydroperiod analysis models are an evolution of the earlier *EC2001* U.S. East Coast and Gulf of Mexico tide model and the S08 and TF01x2 Southern Louisiana storm surge models (Mukai et al. 2002; Westerink et al. 2007b; Ebersole et al. 2007). These models all incorporate the western North Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea to allow for full dynamic coupling between oceans, continental shelves, and the coastal floodplain without necessitating that these complicated couplings be defined in the boundary conditions. The models extend the coverage of these earlier models to geographically include all the floodplains of Southern Louisiana and Mississippi. In addition, improved feature definitions, surface roughness definition, wave radiation stress definition, and grid resolution were all incorporated into the models.

The development of an accurate unstructured grid storm surge model of Southern Louisiana and Mississippi requires appropriate selection of the model domain and optimal resolution of features controlling surge propagation. All five hydroperiod mesh domains, shown on Figure 3, have an eastern open ocean boundary that lies along the 60° W meridian, extending south from the vicinity of Glace Bay in Nova Scotia, Canada, to the vicinity of Coracora Island in eastern Venezuela (Westerink et al. 1994; Blain et al. 1994; Mukai et al. 2002; Westerink et al. 2006; Ebersole et al. 2007). This domain has a superior open ocean boundary that is primarily located in the deep ocean and lies outside of any resonant basin. There is little geometric complexity along this boundary. Tidal response is dominated by the astronomical constituents, nonlinear energy is limited due to the depth, and the boundary is not located near tidal amphidromes. This boundary allows the model to accurately capture basin-to-basin and shelf-to-basin physics.

Much of the domain is bordered by a land boundary made up of the eastern coastlines of North, Central, and South America. The highly detailed/resolved region extends to the west of Beaumont, Texas, and to the east of Mobile Bay, Alabama. These areas in Texas and Alabama were included in order to incorporate terrain complexities that affect Louisiana and Mississippi to realistically attenuate and laterally spread into the adjacent states. In Southern Louisiana and Mississippi the domain includes a large overland region that is at risk for storm surge induced flooding. The northern land boundary extends inland and runs along high topography or major hydraulic controls. From Texas, the land boundary runs along the 30- to 75-foot land contour to Simmesport, Louisiana. The boundary was positioned such that lower lying areas, including the Golden Triangle Marsh, and the adjacent highlands were included. It is critical that boundary location and boundary condition specification do not hinder physically realistic model response.

We have incorporated critical hydraulic features and controls that both enhance and attenuate tidal response. Rivers and channels can be conduits for flow propagation far inland. Topographical features such as levee systems stop flow and can focus storm surge energy into local areas, resulting in the amplification of storm surge. Floodplains and wetlands cause attenuation of flood wave propagation. In Louisiana, there are many interconnected features including deep naturally scoured channels, wetlands, and an extremely extensive and intricate system of river banks, levees, and raised roadways. We have incorporated the Mississippi and Atchafalaya rivers, numerous major dredged navigation canals including the GIWW, IHNC, MRGO, Chef Menteur Pass, Rigolets, and lakes and bays including Lake Pontchartrain, Lake Maurepas, Lake Borgne, Barataria Bay, Timbalier Bay, Terrebonne Bay, Lake Salvador, Lac des Allemands, Atchafalaya Bay, Vermilion Bay, White Lake, Grand Lake, Calcasieu Lake, and Sabine Lake. In Mississippi, we have incorporated St. Louis Bay, Biloxi Bay, Pascagoula Bay, and Mobile Bay as well as the connected channels. All significant levee systems, elevated roads, and railways have been specifically incorporated into the domain as barrier boundaries. These raised features are represented as either internal barrier boundaries or as external barrier boundaries when they are at the edge of the domain and compute overtopping using weir formulae. However, for the hydroperiod tidal simulations, as well as the wind sensitivity simulations, no overtopping occurs.

The computational grid has been constructed to provide sufficient resolution for the tidal, wind, atmospheric pressure, and riverine flow forcing functions from the ocean basins to the coastal floodplain. Efficient and effective resolution of tidal response within the basins and on the shelf is determined by tidal wavelength and topographic length scale criteria. Based on propagation of the predominant tidal wavelength for the M_2 tide, the wavelength criteria determines the ratio of wavelength (•) to node spacing • x. A minimum wavelength-to-grid spacing ratio $\bullet_{M_2}$/ (• x) of at least 50 is required, and more satisfactory is closer to 100 (Westerink et al. 1994; Luettich and Westerink 1995). The grid also has increased resolution at the shelf break guided by a topographic length scale criteria in order to capture the higher localized wave number content (Hagen et al. 2000; Hagen et al. 2001).

The grid design provides localized refinement of the coastal floodplains of Southern Louisiana and Mississippi and of the important hydraulic features. The level of detail in Southern Louisiana and Mississippi is unprecedented in the hydroperiod meshes, with nodal spacing reaching as low as 26 feet in the most highly refined areas around the proposed barrier. Unstructured grids can resolve the critical features and the associated local flow processes with orders of magnitude fewer computational nodes than a structured grid because the latter is limited in its ability to provide resolution on a localized basis and fine resolution generally extends far outside the necessary area. The meshes are refined locally to resolve features such as inlets, rivers, navigation channels, levee systems, and local topography/bathymetry. However, narrow channels were not over-resolved in order to control computational cost. A finer level of resolution creates additional nodes, elements, and thus calculations per time step. In addition, a smaller time step is needed within the ADCIRC model in order to accommodate for the high spatial resolution. A Courant, Friedrichs, Levy parameter less than 0.5 is desired when running the ADCIRC model. A second important attribute of channel meshes is the placement of a minimum number of nodes across a channel. When possible, at least three to five nodes were placed across a channel for two reasons. First and foremost, channels require high resolution in order to adequately capture bathymetric characteristics. Second, multiple nodes are placed within the channel to prevent the ADCIRC wetting and drying algorithm from artificially reducing the conveyance of the channel.

The unstructured grid is easily identified by the variation from the large elements in deep water to the very highly refined area around Southern Louisiana and Mississippi (Figure 3). This wide range of element sizes demonstrates the significant advantages of unstructured numerical methodologies: application of resolution is governed by local geometric and local flow scales, and the cost of the computation is minimized while accuracy is maximized. Furthermore, even with the large, basin-scale domain it is possible to apply very high resolution within coastal regions in order to provide appropriate scaling of features and flow in these areas. The hydroperiod computational grids contain more than 2,130,000 nodes and 4,180,000 elements. Grid resolution varies from approximately 12 to 15 miles in the deep Atlantic Ocean to about 26 feet near the proposed barrier. The high grid resolution required for the study region leads to a final grid with more than 90 percent of the computational nodes placed within or upon the shelf adjacent to Southern Louisiana and Mississippi, enabling sufficient resolution while minimizing the cost of including such an extensive domain. Therefore, use of a large scale domain only adds 10 percent to the computational cost of the simulations. The result, however, is the application of highly accurate boundary conditions and full dynamic coupling between all scales from basins to inlets.

3.4 Bathymetric/Topographic Definition

Geometry, topography, and bathymetry in the SL15 model, thus the hydroperiod models, were all defined to replicate the prevailing conditions in August 2005, prior to Hurricane Katrina with the exception of some of the barrier islands and area between Lake Pontchartrain and Lake Borgne that were included as post-Hurricane Katrina September 2006 configurations. The bathymetric and topographic data were interpolated to the SL15 computational mesh by moving progressively from the coarsest and deepest to the finest and shallowest areas of the computational domain.

In order to simplify the specification of accurate tide and hurricane storm surge boundaries, the Gulf of Mexico and a portion of the Atlantic Ocean were included in the computational mesh. Open ocean bathymetric depths were first interpolated from a 5 degree x 5 degree regular grid based on the ETOPO5 values. The Digital Nautical Charts (DNC) bathymetric values were then applied over much of the Atlantic, Gulf, and Caribbean. Subsequently, bathymetric values were applied using the National Oceanic and Atmospheric Administration (NOAA) depth-sounding database. Thus, bathymetric values were applied with a priority/availability system with preference being given to the NOAA sounding database, then the DNC database, and then the ETOPO5 database. This preference is related to the accuracy of each database (Mukai et al. 2002). Bathymetric values were evaluated at computational nodes using an element-based gathering/averaging procedure instead of a direct interpolation procedure. The gathering/averaging procedure searches for all available sounding/bathymetric survey values within the cluster of elements connected to one specific node. It then averages these values and assigns the average value as the depth/bathymetric elevation to that node. This gathering/averaging procedure essentially implements grid scale filtering to the bathymetric data and ensures that bathymetry is consistent with the scale of the grid. Bathymetry was locally checked with available NOAA navigational charts; in regions with missing or incorrect data, supplemental data from the USACE MVN, U.S. Geological Survey (USGS), or National Ocean Service (NOS) bathymetric charts was applied. Bathymetry was typically specified to tidal mean lower low water (MLLW) and then adjusted to North American Vertical Datum 88 (NAVD88) (2004.65) by adding the difference between NAVD88 (2004.65) and MLLW at the nearest NOAA datum location (on average over the region adding 0.44 foot) so that the correct datum was defined.

Inland bathymetry for southern Louisiana and Mississippi was largely taken from regional bathymetric surveys from the U.S. Army Engineer District, New Orleans and other sources. Inland lakes and other channels were defined using the extensive data sources outlined in the FEMA report (Westerink et al. 2007a). Particular care was taken to define bathymetry for the channels. Due to the scales, averaging methods were not appropriate and background base grids were prepared directly from the sounding tracks that were then used to interpolate channel values. Quality checks were also performed on the bathymetry prior to putting the model into production. First and foremost, the connectivity of the flow features was inspected. Transitions between features were smoothed so that flow was not cut off or re-routed in a physically inaccurate manner. Next, the channels themselves were quality checked for smoothness. In sections of some channels, especially at channel intersections, survey data were not available or thorough enough to correctly capture the intersection bathymetry. The presence of steep, fluctuating gradients is not physically realistic. Thus, ridges artificially interpolated into the channels were removed in order to represent the channel conveyance in a manner more analogous with the channels' natural state. Lastly, grid quality checks were done within the mesh module in order to ensure that the grid quality leads to accurate numerical performance.

Topography in both Louisiana and Mississippi was obtained predominantly using the Atlas lidar in Louisiana and the Mississippi Coastal Analysis Project lidar in Mississippi as specified in the FEMA report (Westerink et al. 2007a). USGS National Elevation Dataset data were applied in the western edge of Louisiana and the portions of Texas and select other regions in the grid as well as described in the FEMA report (Westerink et al. 2007a). Where no data were available in the wetlands, the Louisiana Gap Analysis Program (LA-GAP) land cover data were applied with assumed topographic heights of 0.80 meter where there is marshland and 0.40 meter where there is water. Grid scale averaging details can be found in the FEMA report (Westerink et al. 2007a).

In addition, USGS post-Hurricane Katrina lidar data were applied to the Chandeleur and USACE post-Hurricane Katrina lidar data were applied to the Mississippi Sound Islands with the exception of the Half Moon Island, Deer Island, and Singing River Island where MARIS data were applied.

The topographic data were applied to the grid by searching for all lidar points within a rectangle defined by the average distance from the node for which we are assigning a topographic value to the connected nodes. This rectangular averaging paradigm was applied because the search algorithms to find all the topographic values work significantly faster than the unstructured grid element cluster gather/averaging schemes used for the bathymetric data. Given the number of on land nodes and the tremendous size of the lidar databases, speed is critical. Finally, we note that the rectangular averaging scheme also effectively implements grid scale averaging to the topographic values assigned to the nodes in the grid.

3.5 Raised Feature Definition

Levee and road systems that are barriers to flood propagation are features that generally fall below the defined grid scale and represent a non-hydrostatic flow scenario. It is most effective to treat these structures as sub-grid scale parameterized weirs within the domain. ADCIRC defines these as barrier boundaries by a pair of computational nodes with a specified crown height (Westerink et al. 2001). Once the water level reaches a height exceeding the crown height, the flow across the structure is computed according to basic weir formulae. This is accomplished by examining each node in the defined pair for their respective water surface heights and computing flow according to the difference in water elevation. The resulting flux is specified as a normal flow from the node with the higher water level to the node with the lower water level for each node pair. For this Study, no overtopping occurred. However, the proper placement of raised features is critical to properly route and impede flow.

3.6 Bottom and Lateral Friction Process

Throughout most of the domain, the standard quadratic parameterization of bottom stress is applied.

In order to model the spatially variable frictional losses we apply a Manning n formulation in order to compute the bottom friction coefficient. Nodal Manning n coefficients are spatially assigned using the LA-GAP, Massachusetts Gap Analysis Program, and National Land Cover Data (NLCD) land type definition and the associated Manning n value defined in the FEMA report (Westerink et al. 2007a). For open ocean, large inland lakes, sheltered estuaries, inland lakes, deep straight inlets channels, deep meandering rivers, and shallow meandering channels, n is assigned to equal 0.02, 0.02, 0.025, 0.025, 0.02, 0.025, and 0.045. We apply a grid scale rectangle surrounding the node of interest and again select all Gap Analysis Program or NLCD based land use values and average their associated Manning n. Again, this effectively implements grid scale averaging for the Manning n selection process. When C_f *values* are computed for a specific node and water column height, a lower limit equal to 0.003 is set.

Momentum diffusion and dispersion due to unresolved lateral scales of motion as well as the effects of depth averaging are accounted for by an eddy viscosity type closure model. A simple version of the standard isotropic and homogeneous eddy viscosity model implemented by Kolar and Gray (1990) is used, where •$_T$ is the spatially variable, depth-averaged horizontal eddy viscosity coefficient. For this simulation, three eddy viscosity values were used. In the oceans, deep lakes, and rivers a value of 5.0 meters squared per second (m^2/s) was found to accurately model flow-stage relationships in the Mississippi and Atchafalaya rivers as well as correctly model the tidal exchange in the Lake Pontchartrain – Lake Borgne system through the Rigolets and Chef Menteur Pass. In marshes, swamps, and regions of overland flow, a value of 50.0 m^2/s was used to account for additional turbulence and associated momentum losses. Finally, in the study region, a value of 2.0 m^2/s was used. The lower value is appropriate in the study region where the elements are very small. The smallest elements used in this area are less than 10 meters in size. In all regions of the domain, it is necessary to define slip conditions at the wet/dry element interfaces because lateral boundary layers cannot be resolved at the defined grid scales and no slip conditions unrealistically restricted flows with the defined grids and lateral eddy viscosity values (Feyen et al. 2000).

3.7 Tide and River Forcing Functions

Water level fluctuations in the ocean's surface due to low frequency phenomena are specified through several forcing functions. First, the open ocean boundary is forced with the K_1, O_1, M_2, S_2, and N_2 tidal constituents, interpolating tidal amplitude and phase from Le Provost's global tidal model based upon satellite altimetry (Le Provost et al. 1998) onto the open ocean boundary nodes. Second, tidal potential forcing that incorporates an appropriate effective earth elasticity factor for each constituent was applied on the interior of the domain for these same constituents (Westerink et al. 1994; Mukai et al. 2002). The nodal factor and equilibrium argument for boundary and interior domain forcing tidal constituents were determined based on the starting time of the simulation (Luettich and Westerink 2004).

The resonant characteristics of the Gulf of Mexico require a period of model simulation in order for the startup transients to physically dissipate and dynamically correct tidal response to be generated. The model is run with tidal spin-up for a minimum of 18 days before the full tidal simulation so that the tidal signal can become effectively established; this spin-up time was determined through testing of model sensitivity to the generation of resonant modes using separate single semi-diurnal and diurnal tidal constituents. A hyperbolic tangent ramp function is applied to the first 12 days of the tidal forcing to minimize the generation of startup transients. The forcing functions were chosen such that the 18-day spin-up component of the simulation corresponded to the final 18 days of August 2007 followed by the second component of the simulation which corresponded to the full 30 days of September 2007.

At land boundary nodes outside of Southern Louisiana and Mississippi, a no-normal flow condition is applied. At land boundaries in Southern Louisiana and Mississippi, no normal flow and external barrier boundaries are specified. At river boundaries, a simple elevation or flux boundary condition would reflect tides and surge waves that are propagating upriver back into the domain. In order to prevent this non-physical reflection from occurring, a wave radiation boundary condition was developed that specifies flux into the domain while allowing surface waves to propagate out (Luettich and Westerink 2003). The radiation condition is based on the relationship between the normal flow and elevation at the boundary.

3.8 Local Mean Sea Level (LMSL) and Steric Water Level Adjustments

Annual sea surface variability in the Gulf of Mexico is significantly influenced by the thermal expansion of surface ocean waters and by other factors including coastal currents, riverine runoff, variability in salinity, seasonal prevailing winds, and atmospheric pressure. Long-term sea level variability has been quantified at various stations throughout the Gulf of Mexico by NOAA (2001). Analysis of the variability and examination of harmonic constituents rendered a regional average of approximately 0.5-foot maximum sea level rise in mid-September above the annual average water level along the Mississippi and Louisiana coastlines (Westerink et al. 2007b).

In order to make the seasonal sea surface adjustment for Hindcast storms, NOAA's long-term sea level station data at Dauphin Island, Alabama, Grand Isle, Louisiana, and Sabine Pass, Texas, is interpolated to the time of landfall of the storm. Thus, for the hydroperiod simulations, an estimated increase in sea surface level of 0.79 foot was utilized.

Initial water levels in all regions are therefore raised at the start of the computation with the combined average regional difference between LMSL and NAVD 88 (2004.65) in addition to the steric increase in water. The adjustment equals 0.44 foot + 0. 79 foot =1.23 feet. These adjustments are specified in the initial conditions, surface elevation specified boundary conditions, and as a defined offset for the open ocean boundary condition in the deep Atlantic Ocean.

3.9 Model Operational Parameter Definitions

For hurricane storm surge inundation, wet/dry parameters that are relatively unrestrictive have been found to be most effective: H_0 = 0.10 m, and U_{min} = 0.01 m s^{-1}.

The applied computational time step in the simulations for the Study is 0.50 second. Previous use of the SL15 model employed a 1.0-second time step; however, due to the increased resolution, the time step was lowered for this analysis.

3.10 Tidal Validation

In order to validate the tidal response of the hydroperiod models, tidal response has been analyzed for the existing conditions model output versus gauge data at Pilots Station East NOAA tide station (8760922), near the Southwest Pass of the Mississippi River. All five model simulations were for September 2007, following an 18-day spin-up. Due to the short time frame of the study, tidal simulations long enough for harmonic decomposition of the tides were not a viable option. Thus, a comparison to gauge data has been completed. The comparison is qualitative in nature to some extent, due to the many local effects inherent in the gauge data that are not accounted for in the tidal simulation, such as daily fluctuations in wind, variations in river flow rate, and precipitation.

The models were forced using seven dominant astronomical tidal constituents on the Atlantic open ocean boundary as well as corresponding interior tidal potential forcing functions. The forced tides include the diurnal O_1, K_1, and Q_1 constituents and the semi-diurnal M_2, N_2, S_2, and K_2 constituents. The SL15 model was forced on the 60 degree W meridian open boundary with O_1, K_1, Q_1, M_2, N_2, S_2, and K_2 astronomical tidal amplitudes and phases interpolated onto the open ocean boundary nodes using data from Le Provost's FES95.2 global model (Le Provost et al. 1998). The Mississippi and Atchafalaya rivers were forced with flow and radiation boundary conditions. Tidal potential amplitudes and the associated effective Earth elasticity factors for the seven forcing constituents are described in the FEMA report (Westerink et al. 2007a). Figure 8 shows the results of the existing conditions model output compared to the observed gauge data. The first 8 days, as well as days 14 through 24, demonstrate that the model phase and amplitude are quite similar. However, the modeled water surface elevation varies from the observed data by as much as 0.20 foot. This offset may be due to local physical factors such as buildup from winds or variance in normal Mississippi River flow. The 48-hour period on both sides of days

12 and 25 reveal both phase and amplitude errors between the model and the gauge data. These errors are likely due to the relatively short length of these tidal simulations.

When the harmonic constituents of a longer (60-day) run using the SL15 model are observed, the phase and amplitude errors are greatly reduced (Westerink et al. 2007b). A full quantitative assessment of the ADCIRC SL15 model's ability to simulate the tides can be seen in the FEMA report (Westerink et al. 2007a). Figures 9 through 14 demonstrate the accurate SL15 model response at South Pass (8760551), Southwest Pass (8760943), and again at Pilots Station East (8760922). Using the similar SL15 mesh, it can be observed that a longer model run results in better correlation between amplitude and phase for the tidal constituents. A longer model run will also limit the effect that short-term local physics will have on the overall convergence of amplitude and phase.

4. Results

4.1 Tidal Inundation Difference Analyses

This Study investigates the spatial and temporal extent of tidal inundation in the "Golden Triangle Marsh" area. Differences in the depth and duration of inundation were examined for each of the design alternatives. Results of the analyses are presented in the following sections.

4.1.1 Inundation Depth Analyses

Figures 15 through 19 illustrate the maximum tidal elevations computed for all five simulations. Elevations range from approximately 1.0 to 1.6 feet NAVD88 (2001). The figures clearly demonstrate the effects on the maximum tide elevation in the marsh areas adjacent to the barrier. The closure at Bayou La Loutre lowers the maximum tidal elevation compared to existing conditions in the MRGO, GIWW, IHNC, and southeast portion of the marsh. However, the levels are lowered generally by less than 0.10 foot. The differences can be seen on Figures 20 and 21. When compared to Scenario 2, Scenarios 3, 4, and 5 generally have lower maximum tidal elevations west of the barrier and in the northern portions of the marsh. Scenarios 3 and 4 water surface elevations are lower by generally 0.10 foot or less, while Scenario 5 maximum water levels are lowered by 0.15 foot or less. Scenarios 3, 4, and 5 raise the maximum water surface elevation by 0.10 foot or less in the southern portions of the marsh and in the MRGO. Figures 22 through 27 demonstrate these variances in the maximum tidal elevation.

The maximum depth of inundation was also extracted from each node in the model run for each scenario simulated. These maximum depths were plotted using a Geographic Information System (GIS). These plots are included as Figures 28 through 32. Existing conditions (Scenario 1) are shown on Figure 28. Maximum tidal depths occurring during the Scenario 1 simulation vary from 0 to 4 feet, with zero inundation occurring at high marsh areas in the vicinity of the proposed barrier, and some greater depths occurring in the Bayou Bienvenue channel.

The difference in tidal inundation depth at each node was calculated for Scenarios 3 through 5, and was normalized to Scenario 2, Base Conditions. The difference plots are shown on Figures 29 through 32. Overall, very little difference is noted in maximum tidal depth when comparing all of the scenarios. The most change in maximum tidal depth occurs in scenario 5. This scenario exhibits an increase in maximum tidal depth of about 0.3 foot on the flood (east) side of the proposed barrier.

4.1.2 Water Surface Elevation Time Series Analysis

Time series were recorded for 12,236 points within the marsh for the Study. Of the 12,236 points, 52 were selected as representative points in the marsh area. Figure 33 is a plan view of the point locations. Hydrographs for all 52 points can be found in Appendix A. Figures 34 through 37 show water surface elevation time series at two point locations between the GIWW and Bayou Bienvenue near the proposed barrier. Vertical lines in the hydrographs symbolize the time in which the ADCIRC model is turning node calculations on and off using the wetting and drying algorithm. Thus, time between vertical lines without a recorded water surface elevation is considered as dry marsh for that duration.

Inspection of Point 236, which is located west of the proposed barrier, demonstrates a longer inundation period for Scenarios 3, 4, and 5 when compared to Scenario 2. Instead of the marsh drying with the tidal cycle, a water surface elevation of approximately 1.1 feet is maintained. The elevation at Point 236 is approximately 0.64 foot, correlating to a depth of approximately 0.35 foot being maintained in a marsh area that dries in Scenario 2.

Point 336, located east of the proposed barrier, shows a change in the time series as well. Much like Point 236, the maximum tide elevation is less for the three IHNC barrier scenarios than in Scenario 2. However, the duration in which the marsh remains wet compared to Scenario 2 is on the order of 7 hours longer for many of the

30 days for Scenarios 3 and 4. Scenario 5, however, shows the marsh being wetted by more than 2 hours less than Scenario 2.

The time series vary considerably for all 12,236 points. Quantitatively, Point 236 is representative of the nature of many of the points in the Golden Triangle, resulting in much longer durations of the marsh being wetted. Nonetheless, it should be noted that some marsh areas on the west side of the proposed barriers also have shorter durations. Similarly, many points east of the proposed barrier demonstrate characteristics similar to Point 336. However, in general, variance in duration between Scenario 2 and the IHNC barrier scenarios is less than 7 hours. At some point locations, a shift in tidal phase is also seen. By and large, the phase shift is 30 minutes or less.

4.1.3 Inundation Duration Analyses

The maximum duration of inundation was computed for each node in the model run for each scenario simulated. These maximum durations were plotted using GIS. These plots are included as Figures 38 through 43. Existing conditions (Scenario 1) are shown on Figure 38. Maximum tidal inundation durations occurring during the Scenario 1 simulation vary from 0 to 30 days, with zero inundation occurring at high marsh areas in the vicinity of the proposed barrier and high areas of marsh around Bayou Bienvenue. Some areas were inundated for all 30 days in the simulation period. Most of these points were in the open water areas in the northern part of the Study area.

The difference in tidal inundation duration at each node was calculated for Scenarios 3 through 5, and was normalized to Scenario 2, Base Conditions. The difference plots are shown on Figures 40 through 43. Overall, very little difference is noted in tidal inundation duration when comparing all of the scenarios. All changes are less than 5 days, or 16 percent, and most changes are 0 to 2 days, or up to 7 percent. The most change in tidal inundation duration occurs in Scenarios 4 and 5. These scenarios exhibit a decrease in tidal inundation duration of about 0 to 5 days in some areas on the protected (west) side of the proposed barrier.

4.2 Spatial Extent of Inundation

The biology of many marsh species is sensitive to inundation. One of the important questions that this study seeks to answer is what is the likely change to the wetted areas for the various configurations. It is also desired to examine if changes in the wetted area are more extensive in the interior region protected by the flood protection structure or in the exterior region on the seaward side of the barrier.

The simulation output of time series of water surface elevation was used to compute total area of inundation in the interior and exterior regions. The representative area and bathymetry are known for each of the output stations. If the simulation output indicates that a station is "wet", a depth is computed. If the depth is greater than a prescribed threshold, then that station's local area is included as a contributor to the total inundation area. Inundation areas were calculated for depths greater than 0.25 foot, 0.5 foot, 0.75 foot, and 1.0 foot. The calculation was repeated separately for protected and exterior regions for each of the scenarios. Time series of interior area are shown on Figures 44 through 47 and the time series of exterior area are shown on Figures 48 through 51. The maximum and minimum of wetted area throughout the 30-day simulation are shown in Table 1 and Table 2 for the interior and exterior regions, respectively. In looking at the differences within the interior region, it can be seen that in comparison to the existing condition and the base condition (with only the La Loutre Closure), the presence of the barrier does reduce the wetted area.

Table 1. Maximum and Minimum of Inundated Area within the Interior Region, in acres.

Interior Area	Existing Case		Base Case		S3		S4		S5	
Depth (ft)	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
0.25	341	657	349	656	404	631	402	634	419	629
0.5	307	653	317	653	365	627	360	629	382	624
0.75	243	617	247	588	280	504	277	517	294	494
1	227	487	231	475	247	441	246	449	251	437

Table 2. Maximum and Minimum of Inundated Area within the Exterior Region, in acres.

Exterior Area	Existing Case		Base Case		S3		S4		S5	
Depth (ft)	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
0.25	5717	9322	5797	9171	5949	9409	5962	9396	5870	9450
0.5	5592	9232	5662	9072	5794	9220	5802	9215	5700	9265
0.75	5041	8655	5141	8477	5217	8501	5221	8493	5152	8525
1	4429	7970	4538	7826	4688	7806	4697	7786	4651	7827

To quantify the degree that the barriers restrict the inundated extents, percentage reductions are computed for the maximum area and the percent reduction in the range of maximum and minimum wetted area throughout the 30-day simulations. The results for the interior region are shown in Tables 3 and 4. Note that there is very little difference from doubling the size of the opening between Scenario 3 and Scenario 4. Scenario 4 does allow more water into the interior region, but it is a small difference. In comparison, closing of the Bayou Bienvenue opening in Scenario 5 makes a much more significant reduction. The difference in wetted area variance is reduced by as much as 41 percent for Scenario 5 which indicates a significant reduction in variability of the wetted area when Bayou Bienvenue is closed. Note also that the wetted areas and percent changes are sensitive to the depth threshold with the largest impact being observed for the areas calculated with the 0.75-foot threshold. Nevertheless, the trends are similar between Scenario 3, Scenario 4, and Scenario 5 for all threshold-depth areas.

Table 3. Percent Reduction in Maximum Wetted Area within the Interior Region.

Depth (foot)	Percent Reduction in Maximum Area		
	Scenario 3	**Scenario 4**	**Scenario 5**
0.25	-3.7%	-3.3%	-4.1%
0.5	-3.9%	-3.6%	-4.3%
0.75	-14.2%	-12.1%	-15.9%
1	-7.3%	-5.5%	-8.2%

Table 4. Percent Reduction in Wetted Area Variation within the Interior Region.

Depth (foot)	Percent Reduction in (Maximum-Minimum) Area		
	Scenario 3	**Scenario 4**	**Scenario 5**
0.25	-25.9%	-24.3%	-31.6%
0.5	-21.8%	-19.7%	-27.7%
0.75	-34.2%	-29.6%	-41.3%
1	-20.6%	-16.8%	-24.1%

The trend is reversed when looking at the exterior region where the presence of the barrier serves to slightly increase wetted area for the low threshold-depths. Inspection of Tables 5 and 6 for the exterior region indicates that inundation in the exterior is not significantly impacted. The impact of the barrier decreases with increased threshold-depth until the change becomes a small decrease or essentially zero change in inundation. The exterior region is much larger than the interior region and much of the region does not experience a change in extent or duration of inundation. The change in inundation is sensitive to threshold-depth but the trends are consistent between Scenario 3, Scenario 4, and Scenario 5. While the changes are small in the exterior, Scenario 5 with the closed Bayou Bienvenue does create the largest impact.

Table 5. Percent Change in Maximum Wetted Area within the Exterior Region.

Depth	Percent Increase in Maximum Area		
	Scenario 3	Scenario 4	Scenario 5
0.25	2.59%	2.45%	3.04%
0.50	1.63%	1.58%	2.12%
0.75	0.27%	0.18%	0.56%
1.00	-0.26%	-0.52%	0.02%

Table 6. Percent Change in Wetted Area Variation within the Exterior Region.

Depth	Percent Increase in (Maximum-Minimum) Area		
	Scenario 3	Scenario 4	Scenario 5
0.25	2.54%	1.76%	6.10%
0.50	0.46%	0.08%	4.51%
0.75	-1.60%	-1.95%	1.08%
1.00	-5.18%	-6.05%	-3.41%

4.3 Tidal Prism

Another criterion that will be used to evaluate the impact of the various barrier configurations is total water volume. As was described for the evaluation of total inundation area, interior and exterior regions are evaluated separately.

The simulation output of time series of water surface elevation was used to compute total water volume in the interior and exterior regions. Using the known area and depth for each of the station output points, the total water volume is calculated by multiplying the depth by the control volume area and summing the contribution from all the stations. In this way, a time series of water volumes in the marsh is computed. The total water volumes for all scenarios are shown on Figure 52 for the interior region. Figures 53 through 55 show the volume differences between the base condition and Scenario 3, Scenario 4, and Scenario 5, respectively. Figures 56 through 59 display the same information for the exterior region.

It should be noted that barriers alter the timing of flood and ebb in the region. This difference in phasing reveals itself in the time series plots of volume differences and seems to suggest a large difference in overall water volumes but actually the water is simply arriving and leaving at slightly different times. Due to the large volumes of water involved, a phase difference of only 15 to 30 minutes in arrival time of the flood/ebb can generate large differences in temporal volumes. Consequently, comparison of maximum, minimum, and average water volumes are computed and presented in Tables 7, 8, and 9 for the interior marsh and Tables 10, 11, and 12 for the exterior marsh.

When a running average of water volume in the marsh is plotted, the average value asymptotically approaches a constant, as would be expected. This can be seen on Figure 60 for the base case and Figure 61 for Scenario 3 as typical results. The trends for the other scenarios are similar. The differences in long-term average volume between the base and Scenario 3, Scenario 4, and Scenario 5 are shown on Figures 62, 63, and 64, respectively. Differences in long-term average water volume for the exterior marsh are shown on Figures 65, 66, and 67. Note that the oscillations damp out as the volume is averaged over a longer time interval. The asymptotical average values are those shown in Tables 9 and 12.

In the interior marsh, the barrier decreases the range of flood and ebb volumes, but even though the maximum is lower and the minimum is higher, the long-term mean quantity of water volume in the marsh is not significantly changed. Note that in Table 9, the difference in the long-term average is less than 20 acre-foot. Considering the total area of the interior marsh is approximately 404 acres, this change in average water volume represents a difference of less than 1 inch of water depth distributed across the region. This difference in volume may be smaller than the precision achievable with present computational resources. Similarly for the exterior marsh, the long-term averages are very close (within 1 percent) of the base values. Thus, the long-term average water volumes should be considered nearly equivalent.

Table 7. Maximum Volume, Difference, and Percent Difference of Volume in the Interior Marsh.

	Base (acre-foot)	Scenario 3 (acre-foot)	Scenario 4 (acre-foot)	Scenario 5 (acre-foot)
Maximum Volume	5,638	5,282	5,350	5,222
Difference	-	-356	-287	-416

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	Base (acre-foot)	Scenario 3 (acre-foot)	Scenario 4 (acre-foot)	Scenario 5 (acre-foot)
Percent Difference	-	-6.3%	-5.1%	-7.4%

Table 8. Minimum Volume, Difference, and Percent Difference of Volume in the Interior Marsh.

	Base (acre-foot)	Scenario 3 (acre-foot)	Scenario 4 (acre-foot)	Scenario 5 (acre-foot)
Minimum Volume	3,474	3,739	3,720	3,821
Difference	-	265	246	347
Percent Difference	-	7.6	7.1	9.9

Table 9. Long-Term Average, Difference, and Percent Difference of Water Volume in the Interior Marsh.

	Base (acre-foot)	Scenario 3 (acre-foot)	Scenario 4 (acre-foot)	Scenario 5 (acre-foot)
Average Volume	4,288	4,302	4,305	4,307
Difference	-	14	17	19
Percent Difference	-	0.33%	0.4%	0.44%

Table 10. Maximum Volume, Difference, and Percent Difference of Volume in the Exterior Marsh.

	Base (acre-foot)	Scenario 3 (acre-foot)	Scenario 4 (acre-foot)	Scenario 5 (acre-foot)
Maximum Volume	75,284	75,233	75,113	75,774
Difference	-	-51	-171	490
Percent Difference	-	-0.07%	-0.23%	0.65%

Table 11. Minimum Volume, Difference, and Percent Difference of Volume in the Exterior Marsh.

	Base (acre-foot)	Scenario 3 (acre-foot)	Scenario 4 (acre-foot)	Scenario 5 (acre-foot)
Minimum Volume	43,101	44,191	44,268	43,729
Difference	-	1,090	1,167	628
Percent Difference	-	2.5%	2.7%	1.46%

Table 12. Long-Term Average, Difference, and Percent Difference of Water Volume in the Exterior Marsh.

	Base (acre-foot)	Scenario 3 (acre-foot)	Scenario 4 (acre-foot)	Scenario 5 (acre-foot)
Average Volume	55,368	55,762	55,758	55,587
Difference	-	394	390	219
Percent Difference	-	0.71%	0.71%	0.40%

The difference between the maximum water volume and the minimum water volume defines the tidal prism. Percentages are computed to show how this volume of water is influenced by the various barrier configurations. Table 13 shows the percent decrease in tidal prism. It can be seen that all three scenarios restrict the tidal prism that reaches the interior marsh region. There is a slight advantage of Scenario 4 over Scenario 3 due to the double capacity of the larger openings. Scenario 5 is the most restrictive of the scenarios.

The percent change in the exterior region is summarized in Table 14. It can be seen that the degree of change is much less for the exterior region than for the interior region. In fact, one observation is that the larger the barrier opening, the greater the impact on the exterior region. Scenario 5, which produces the greatest impact on the interior region, produces the least impact on the exterior region.

Table 13. Percent Change in the Interior Tidal Prism.

Percent Change in Peak Volume		
Scenario 3	**Scenario 4**	**Scenario 5**
-28.71	-24.66	-35.25

Table 14. Percent Change in the Exterior Tidal Prism.

Percent Change in Peak Volume		
Scenario 3	**Scenario 4**	**Scenario 5**
-3.54	-4.16	-0.43

4.4 Wind Effect Analysis

In order to quantify the effects of typical seasonal winds on the water surface elevation in the area of the proposed barrier, 1-day simulations (subsequent to a half-day ramp) were run on each of the five geometries analyzed. For all geometries, constant westerly and easterly winds of 10 mph were applied. Reported wind values for September 2007 at the nearby Lakefront Airport were a maximum of 22 mph, minimum of 0 mph, and an average of 9.0 mph. New Orleans International airport and Houma airport were also analyzed with average winds of 6.3 mph and 5.1 mph, respectively. A conservative average wind estimate of 10 mph was agreed upon with members of HPO for our analysis.

Figures 68 and 69 show the resulting maximum water surface elevations for Scenario 2. Water surface elevations are approximately 1.05 feet in the Study area for easterly winds. Likewise, water surface elevations are approximately 0.80 foot for westerly winds. In general, a difference of approximately 0.20 to 0.25 foot exists. Due to the similar geometries of the five scenarios, the maximum water surface elevations and associated differences are quite comparable. Thus, it is assumed that seasonal winds can affect water surface elevations by as much as 0.25 foot for all scenarios.

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Appendix A

Hydrographs